EDDY DISSIPATION MODEL FOR MODELING OF TURBULENT NON-PREMIXED COMBUSTION WITH RADIATION EFFECT USING OPENFOAM

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To my beloved family and friends

ABSTRACT

The Eddy dissipation model is one of the popular turbulent combustion models owing to its reasonable computational cost and accuracy. The purpose of this study is to implement the eddy dissipation model in OpenFOAM which is an open source code. It was implemented in many commercial CFD codes but it is the first time to be implemented in OpenFOAM. The model was implemented in new solver; EdmFoam. This new combustion solver was linked to radiation models library in OpenFOAM. EdmFoam solver was tested in modeling two different types of flames; jet flame and swirling flame. Each case was performed with and without radiative heat transfer modeling. The results were extensively compared against experimental measurements for temperature, mixture fraction and flame length. The predicted values showed that the model was implemented successfully. The results have a reasonable agreement with the experimental results. The results prove that a strong relation between the eddy dissipation model and the turbulence model behavior exists. The numerical predictions showed the importance of radiation modeling for the combustion cases. .

ABSTRAK

Model peresapan Eddy ialah salah satu model pembakaran gelora paling popular kerana ketepatannya dengan kos yang munasabah. Tujuan kajian ini ialah untuk melaksanakan model peresapan pusar menggunakan OpenFOAM yang menggunakan kod sumber terbuka. Kajian serupa ini telah banyak dilaksanakan menggunakan kod CFD komersial yang lain. Namun, ini adalah usaha pertama menggunakan kod OpenFOAM untuk kajian ini. Model ini telah dilaksanakan di penyelesai baru; EdmFoam. Penyelesai pembakaran baru ini telah dirangkaikan dengan perpustakaan model radiasi di OpenFOAM. Penyelesai EdmFoam telah diuji pada dua jenis model api, api jet dan api berpusar. Setiap kes dilakukan dengan dan tanpa pemodelan pemindahan haba sinaran. Keputusan yang diperolehi dibandingkan secara meluas dengan keputusan pengukuran suhu, pecahan campuran dan panjang nyalaan. Nilai yang diramalkan menunjukkan bahawa model yang berjaya dilaksanakan dengan jayanya. Keputusan menunjukkan juga hubungan yang munasabah dengan keputusan uji kaji. Keputusan membuktikan bahawa hubungan yang kuat antara model pelesapan pusar dan tingkah laku model gelora wujud. Ramalan-ramalan berangka menunjukkan kepentingan pemodelan radiasi bagi kes-kes pembakaran.

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
EDM	Eddy Dissipation Model
GPL	General Public License
LES	Large Eddy Simulation
OpenFOAM	Renormalization Group
prePDF	Presumed Probability Density Function
RAS	Reynolds Stress Method
SAS	Scale Adaptive Simulation
VHS	Volume Heat Source

CHAPTER 1

INTRODUCTION

1.1 Overview

Although the origin of fire making is a mystery, it played a huge role in the progress of our civilization development. The fire was used directly for heating, cooking and as defense weapon against the wild animals. It was just a matter of time that the idea of controlling the fire appeared. Combustion is the controlled version of the fire. Controlling the fire means how to start or stop a fire and how to control precisely the temperature. Combustion can be considered as an efficient controlled fire.

Combustion of the fossil fuels is the main source of energy on earth. The magic of transferring chemical energy to thermal energy leaded the industrial revelation. At that time engineers and scientists did not know a lot about the combustion process. The chemical reaction was known and how to control it. That was enough for engineers to develop their machines. They started to use any available fuel on earth. That makes engineers fully aware about designing combustors for different applications. They developed the internal combustion engines, gas turbines and boilers. By the time and the rise of the fuel prices, the idea of how makes the combustion more efficient to save more fuel has been appeared. That leads scientists to try to understand more about the physical phenomena of combustion. Today not only the high prices of fuel that pushes humanity to search for more efficient ways of fuel combustion but also the harmful effect of combustion emissions on the planet. Although the tremendous research in green energy, still the direct way to save the planet is reducing the emissions by more efficient combustion.

Towards more understanding of the combustion in various applications, another complex physical phenomenon which is coupled to the combustion in almost all the industrial applications had been appeared, it is turbulence. Turbulent combustion combines two branches of physics; the chemical reaction and turbulence. Those branches are far away from being fully understood. They still have many unanswered questions even the basic ones. Turbulence is one of the unsolved problems in the classical physics. There is no such theory to describe the whole turbulence phenomena.

The general view is that turbulence causes the formation of eddies of many different scales. Most of the kinetic energy of the turbulent motion is contained in the large scale structures which is extracted from the main flow. The energy transfers from the turbulence large scale eddies to smaller scale eddies. This process creates smaller and smaller eddies which produces a hierarchy of eddies. Eventually this process creates eddies that are small enough that molecular diffusion becomes important and viscous dissipation of energy finally takes place. The scale at which this happens is the Kolmogorov length scale [1]. It is clear from the above description for turbulence energy cascade that the small eddies are universal for any turbulent flow, in contrast to the large eddies which are highly depending on mean flow and case geometry. Here appears the complexity of turbulence that it is not universal in our point of view, so there are no such general theory to describe the turbulence.

Combustion process requires a molecular mixing between the fuel and oxidizer. In turbulent combustion the mixing processes depends on the turbulent mixing which takes place at macro scale level. The chemical reaction could be assumed to be single step reaction which takes place at certain level or multi- step reaction with many time scales. Turbulence has many macro scales and combustion has many micro scales expect for very slow chemistry, what the relation between them. Turbulence enhances the mixing through the eddy break up process which enhances the combustion [2, 3]. The combustion releases heat which increases the instability and turbulence. Although these effects are observed experimentally many times, it is unclear how these effects could be modeled. Navier-stokes equations describe the macro scale properties only, which is the main challenge in turbulent combustion modeling.

Computational fluid dynamics uses the flow governing equations which are continuity equation, momentum equations, energy equation and the equation of state. They govern any Newtonian fluid flow field; whether laminar or turbulent and steady or unsteady. In turbulent flow cases, there are three options to solve the equations. First one is the Direct Numerical Simulations (DNS) which calculate all the turbulence scales but it requires a very fine grid and very small time step which is computationally highly expensive and limited to simple cases only. The second option is using Reynolds Averaged Navier-Stokes models (RAS) such as the standard K-epsilon model. RAS models are extensively used in many engineering fields due to it reasonable computational cost and satisfactory results. The third option is Large eddy simulation (LES) which solves complete Navier-stokes equations for the large eddies and models the small eddies. It is more expensive than RAS models but less than DNS. In this work, only RAS models are used due to the available computational resources and the model implementation.

Concerning combustion modeling, more equations are required to describe the concentration and reaction rate of each specie in order to close the transport equations. More source terms are added to the energy equation to take into account the heat release due to combustion.

Generally speaking combustion models are classifieds based on two parameters; the flame type and chemistry speed [2-5]. There are models especially formulated for each flame type; premixed, non-premixed or partially-premixed and there are models that can be used for different types of flames with minor or major modifications. Regarding the chemistry speed models, these are classified to finite rate chemistry models and fast chemistry models. Finite rate chemistry models solve the detailed reaction chemical kinetics which is computationally expensive. In contrast to the fast rate chemistry model which assumes one or two step reaction assuming that the reaction rate is very fast with respect to turbulence time scale. The assumption of fast chemistry is valid in practical combustion cases where combustion is very fast [6, 7]. The current study focuses on the eddy dissipation model which is a fast chemistry model assuming single step reaction for non-premixed flames [8-10]. It is also suitable for premixed flames modeling with minor modifications. The eddy dissipation model is one of the most popular combustion models in the engineering field and it is also a valuable research tool. A detailed description about the model and it applications will be discussed in the next chapter.

There are many commercial CFD codes around the world. These codes have many common features. They are suitable to be used in many scientific fields and developed by highly expert teams. Commercial CFD codes are tested by many users in different cases. They are user friendly. That is the bright side of the story. On the other hand they are very expensive, very hard to develop –almost impossible in many cases- and they are black boxes. The users are not allowed to check how the models are really implemented in the code. The only source of knowledge is the user guide which does not give the whole truth. Therefore there are in house codes in many research centers which are devolved based on their needs. These codes are private and classified in many cases. Even if these codes are shared, it will be hard to either develop or understand the code. Simply they are lacking the user guides and support. They are not designed to be reused by different users. The above pros and cons of commercial and in house customized codes motivated the idea of open CFD source codes such as OpenFOAM.

OpenFOAM (Open Field Operation and Manipulation) has attracted much attention recently because it is an open source code designed for continuum mechanics applications specially CFD applications. It is a C++ toolbox based on object oriented programming. That makes OpenFOAM sustainable in terms of reuse and development by many users all around the world, in contrast to the single block programming codes which are very hard to develop or even understand. OpenFOAM is released under the GPL (General Public License). OpenFOAM gives a flexible framework which combines all the required tools for solving any CFD problem. This framework consists of enormous groups of libraries for different mathematical, numerical and physical models. Linking the mathematical/numerical tools with the physical models in a main C++ function produces different solvers and utilities. OpenFOAM, undoubtedly, opens new horizons for CFD community for efficient models to be devolved, allowing the industrial sectors to be updated with all new models without any delay for waiting the new models to be implemented in the commercial CFD codes.

1.2 Problem Statement

Motivated by the importance of the eddy dissipation model as an engineering tool and the capabilities of OpenFOAM, it was decided to implement the eddy dissipation model in OpenFOAM. Until the present moment, an eddy dissipation model implementation in OpenFOAM has not been reported in open literature. This work reveals the implementation of the eddy dissipation model in OpenFOAM. The newly developed OpenFOAM solver (EdmFoam) is linked to radiation modeling library to be capable of modeling radiative heat transfer during the combustion process.

1.3 Objective

The objective of this study is to implement the Eddy dissipation model in OpenFOAM to make new combustion solver called EdmFoam. Then the results will be verified against experimental data from the literature. Also new EdmFoam solver should be capable of modeling radiative heat transfer due to its importance in combustion modeling.

1.4 Scope of Research:

1 Investigating the current available combustion models in OpenFOAM.
2 Selecting one of the available combustion solvers in OpenFOAM as a starting point for developing the new solver.
3 Defining the required developments for the selected solver to reach the study objectives.
4 Programing the eddy dissipation model in the new EdmFoam solver.
5 Linking the new solver with radiation models library in OpenFOAM and apply and required modifications.
6 Comparing the EdmFoam solver results (radiation modeling on/off) against available experimental data for jet and swirling non-premixed flames.

1.5 Structure of Thesis

This thesis contains seven chapters including the present one. The second chapter provides theoretical background of the turbulent combustion modeling. The third chapter is a general overview of available combustion solvers in OpenFOAM. It is also include a full description of rhoReactingFoam model which is the starting model of the new solver EdmFoam. The fourth chapter descries in details the new solver EdmFoam. The fifth chapter and sixth chapter present numerical simulations for jet and swirling non-premixed flames respectively. Finally, the eighth chapter summarizes the findings of this research and recommendations for future work.

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